Net-Shape Processing Applied to Aero-Engine Components

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ABSTRACT

Relatively few of the many net-shape processing routes have the potential for use in the manufacture of aero-engine components. Constraints can range from deposition rate, material cost and availability, reproducibility, consistency in properties, and specification difficulties. However those processes that do fulfil the required criteria can have considerable benefits for aero-engine manufacturers and not just in terms of reduced supply and operational costs. For example, some materials are suffering from long lead times and rising prices due to a high demand from rapidly expanding economies around the world. The increased fly-to-buy ratios that can be achieved by net-shape manufacturing can alleviate supply problems whilst still applying pressure to reduce component cost. It is also possible to use fine detailed repair processes to extend the life of used components thus easing the supply of spares as well as reducing life-cycle costs. The net-shape processing being applied to aero-engine components will be discussed in terms of specific examples.

1.0 INTRODUCTION

The proportion of originally purchased material that is finally built into an aero-engine, the so called buy-to-fly ratio, can be as low as 10% which means that 90% is reduced to relatively low-value scrap. Thus, considerable excess time and money is used to make the raw material and even more is used to form then machine the final product shape. Although some cost can be off-set by selling purposely identified and segregated waste to be recycled, and somewhat less of the cost can be offset by selling lower grade mixed scrap to the steel industry, there is still a significant amount of fine material engrained in consumable machining waste or in the form of oxide scale that ends up in a landfill site. A crude estimate of the quantity these types of waste across the industry is 30%, 50% and 20% respectively that return less than 10% of the original purchase price in scrap value but this is probably counteracted by the overall handling costs and disposing of the unrecoverable waste.

Wasteful manufacturing is no longer sustainable in the aero-engine business as the cost of key materials such as titanium and nickel alloys is escalating, fuelled by the seemingly inexhaustible requirements of the world's strongly developing Asian economies. There are also tough ecological initiatives being introduced across the world aimed at reducing the impact of manufacturing on the environment particularly in terms of energy consumption, use of resources and waste pollution. There are even tougher targets that have to be met for engine efficiencies and gas emissions such as stated by ACARE (Advisory Council for Aeronautics Research in Europe) where for example exhaust carbon dioxide is to be reduced to 50% by 2020. The obvious response to all these issues is to convert to net-shape or near net-shape manufacturing techniques where fly-to-buy ratios can be around 85-90% together with the potential for superior design and application developments.

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Due to advances in raw material production by chemical and electrochemical techniques both in the UK and the US, there is also the exciting prospect that net-shape processing can take advantage of relatively cheap alloy powders soon to be on the market. The cost of alloy powder could be reduced by as much as two-thirds with the improvements in purity and size distribution giving significant additional benefits notably in the forms of low segregation and an even greater reduction in the risk of defects.

1.1 Net-Shape Technology

Net-shape and near net-shape, subsequently referred to as just net-shape, manufacturing can be defined as 'the manufacture of a component or section of a component by consolidating material with minimal loss or wastage'. Two types of net-shape manufacture are envisaged; Additive processes based on high energy sources to consolidate wire or powder, for example, shape metal deposition (SMD) and direct laser deposition (DLD); Temperature and pressure activated consolidation of powder or fabricated structures, for example, powder HIP'ing (PHIP) and metal injection moulding (MIM).

The main benefits to be obtained by net-shape manufacture are:

- **Reduced Material Cost** Most of the material in the form of wire or powder is used to directly build the component shape with little overstock or other wastages.
- **Reduced Time to Market** Where necessary tooling can be readily produced from CAD files, alternatively the process can directly use CAD files to construct the component. Either way component manufacture is faster than conventional processing and thus reduces lead times and can fulfil the important role of rapid prototyping.
- **Reduced 'Removal' Operations** Heavy machining or roughing operations are eliminated and finish machining is kept to a minimum which results in less swarf, low energy consumption, and less work in progress (WIP) together with associated lower risk of scrapping and enhanced rapid prototyping capability.
- **Repair Capabilities to Support Aftermarket** A major application is in component repair which will lower total life cycle costs.
- **Enhanced Product Opportunities** The characteristics of net-shape manufacture offer novel design features such as integrating components and graded functionality.

2.0 ADDITIVE MANUFACTURING

Additive manufacturing can be sub-divided using the type of high-energy heat source and the material form as shown in the blue areas of figure 1. Commercial equipment is available for these techniques and the different mechanisms are described in relation to Rolls-Royce elsewhere in this conference.

The prime current aero-engine applications are in repair and in forming protrusions on larger sections. Replacement tips on blades to extend component life is now an established direct laser deposition technique and is likely to play an important economic role in the introduction of bladed disks into aero-engines in the near future. Shaped metal deposition is already used to add thicker feet on outer guide vane (OGV) forged sections to reduce material usage and to decrease the number of forging operations, and full component production has even been demonstrated, such as the casing in figure 2. However further development is considered necessary before these additive manufacturing techniques can be included in mainstream component manufacture, and rapid prototyping remains the most promising next stage in their evolution. A major issue is how to achieve an accurate surface finish without recourse to complete surface machining or the use of expensive fine alloy powder. Another problem stems from consistency in production and how to ensure a stable microstructure and thus material properties that can vary throughout the component due to continuously changing process conditions, particularly cooling rate. More important

is how the components can be economically and non-destructively inspected to demonstrate their integrity when current methods are reliable to just 0.25 mm. The answer probably lies in more advanced heat sources coupled with sophisticated automated process control.

	Material Form		
Heat Source	*Powder Stream*	*Powder Bed*	*Wire*
Laser	LENS POM	Trumpf	DLW
Electron Beam	x	Arcam	CVE
Electric Arc	x	x	SMD

Figure 1: Additive Manufacturing Methods Differentiated by Heat Source and Material.

Figure 2: Shape Metal Deposited Trent 800 Casing Demonstration.

3.0 CONSOLIDATION PROCESSES

Consolidation processes appear to be the most promising net-shape manufacturing method for near-term main stream component manufacture and is therefore the main emphasis of this report.

Cold pressing followed by sintering is normally for difficult materials such as reactive and hard compounds used in machine tools and does not have an obvious direct aero-engine application. It is with Net-Shape Powder HIP'ing and Metal Injection Moulding methods where most benefits are considered to lie for military engine applications.

3.1 Net-Shape Powder HIP'ing

Hot isostatic pressing (HIP) of powders has been developed in Europe and USA over the last decade for aero-space components. The production of nickel alloy aero-engine discs has focused on pancakes that are subsequently forged to shape to achieve the integrity necessary for critical components. Components for spacecraft were produced to near net-shape but significant machining was still required due to the large allowances on the post-HIP shape. Recent advances permit large complex net-shape components to be manufactured that just need skim-machining of those surfaces with high tolerances. In addition, the cleanliness, hence the life of powder components has dramatically improved through the efficient handling procedures developed during the 1990's. The technology is thus ready for aero-engine applications where either excessive machining and therefore cost is currently incurred or where other processing routes are not possible due to the nature of the material [1,2].

The process consists of computer modelling a suitable powder vessel or tooling that accounts for powder consolidation and thermal expansion during HIP'ing. This vacuum tight vessel is constructed from a readily removed consumable material such as mild steel. The vessel is vibration filled with powder whilst being heated to drive off water and hydrocarbons, then the vessel's filling tube is sealed under vacuum. Following HIP'ing of the whole assembly, the external mild steel shell that will have deformed to consolidate the powder is removed by rough machining and/or pickling to reveal the net-shape component. The key to producing net-shape is a combination of valid computer modelling of the shape of the pre-HIP powder envelope, and controlled powder filling of the container to ensure a consistent packing density. In reality, one or two iterations are necessary involving judicious minor changes to the vessel shape, and higher tolerance surfaces are achieved by using locally stiffer sections.

Current consumable tooling can be either thin-walled or thick-walled mild steel. The thin-walled tooling is cheaper to form, join and remove and is generally used for larger components where tolerances are of the order of millimetres. The thick-walled tooling gives a more accurate component definition generally to within 0.3mm and to within 0.1mm for important surfaces, however the cost of tooling is more expensive and so too is the cost of removal. Thus there is a need to develop an economic yet accurate form of tooling before this method of manufacture can become established for volume applications.

3.1.1 Net-Shape Powder HIP'ing; Compressor Casing

Rolls-Royce has recently demonstrated the manufacture of a 0.7m diameter Ti6/4 HP front casing for the V2500 which is a 2-stage engine similar to military units and consists of numerous protrusions such as end and split flanges, webbed bosses for variable guide vanes, and location platforms, see figure 3. This collaboration with Aubert-Duval, Laboratory of New Technologies (LNT) and Birmingham University was very successful and achieved the required shape within two tooling iterations, figure 4. Subsequent machining operations were reduced to just mating faces such as the flanges, bosses and internal diameter and constituted a tenth of the current machining time performed on ring-rolled forgings. The major advantages of this powder HIP'ing process are that lead times can be reduced by at least a half and subsequent machining can be carried out with light fixturing, both of which make it a strong candidate for prototype manufacture. Mechanical properties were also superior to forging, see following section, however the process suffers from being relatively expensive in terms of cost and environmental impact, mainly due to the cost of machining the mild steel tooling and having to pickle the mild steel away in acid baths, figure 5. For this reason, more efficient methods of powder HIP'ing such components are being investigated at the IRC, Birmingham University based on reusable and recyclable tooling.

Figure 3: V2500 Front HP Compressor Casing Machined from a Ring-Rolled Forging.

Figure 4: Net-Shape Ti6/4 Powder HIP'ed V2500 Front HP Compressor Casing.
Figure 5: Mild Steel Tooling Partially Dissolved from Powder HIP'ed V2500 Casing.

3.1.2 Net-Shape Powder HIP Mechanical Properties

The microstructure of powder consolidated Ti6/4 is a very fine distribution of beta phase, shown dark in figures 6, that is isotropic unlike that of wrought material. This results in a relatively small mechanical property scatter band where, although the average value is lower than that of the wrought material, the minimum (3-sigma) level is in fact higher, which means there is an effective property improvement since design is always based on the minimum value, see figure 7. Notably there is a significantly higher tensile elongation of over 20%, i.e. around double that of wrought, and this is particularly useful for casings where containment is related to a power of this value. Similarly, fracture toughness of powder consolidated Ti6/4 is of the order of 90 Mpa.m$^{0.5}$ which is double that of the wrought alloy, and is even better than cast Ti6/4 which has long been considered best for toughness due to the tortuous route that a crack must follow through its microstructure. A massive underlying benefit of powder consolidated material is that it's isotropic and consistent mechanical properties mean that future material specifications could be reduced to just one per alloy, and not the current one per processing route for each component which can be a large cost burden when introducing new components.

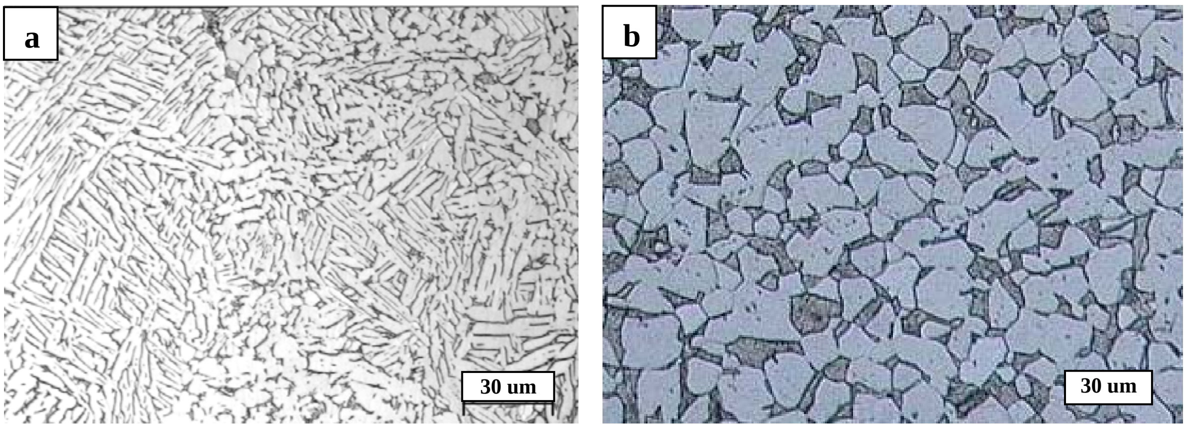

Figure 6: Microstructure of Ti6/4 (a) Powder HIP Consolidated at 920^{o}C Compared to (b) Rolled Plate.

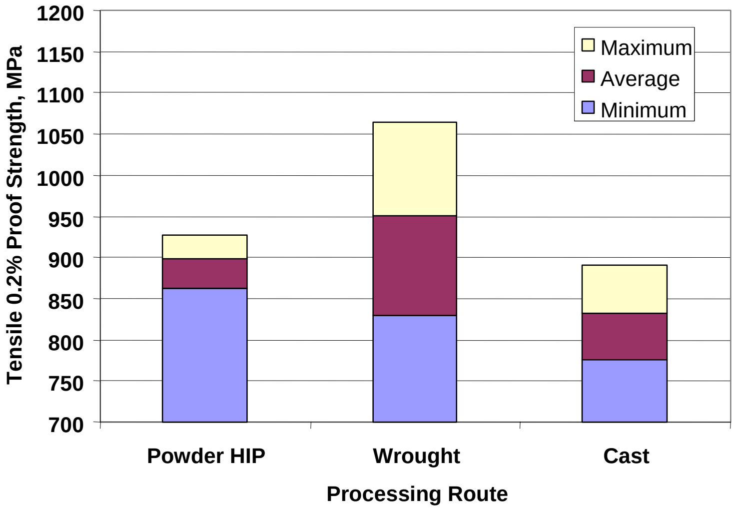

Figure 7: Comparative Strength of Ti6/4; Powder HIP'ed, Wrought and Cast Alloy.

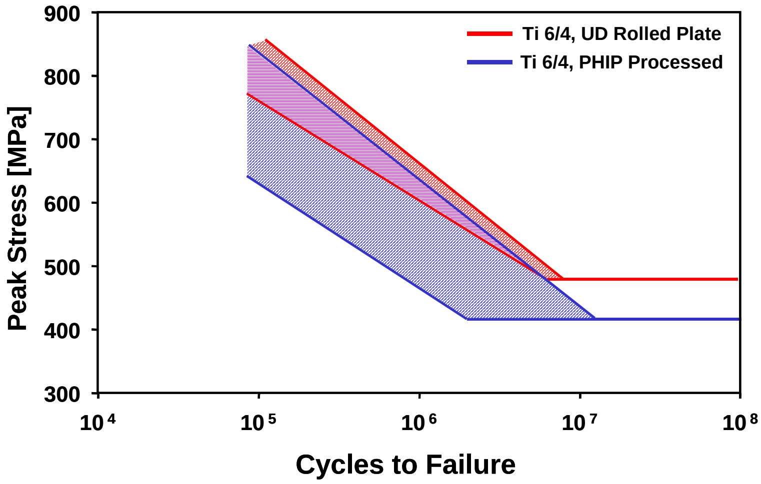

Figure 8: Fatigue Strength of Ti6/4; Powder HIP'ed against Uni-Directionally Rolled Plate.

Arguably the most important mechanical property for aero-engine components is fatigue and this is where powder and process cleanliness is critical for powder HIP consolidation. Results recently generated by Swansea University shown in figure 8 show that powder HIP consolidated Ti6/4 PREP (Plasma Rotating Electrode Process) powder has good fatigue properties that even overlap with the range of uni-directionally rolled plate which is processed to give a relatively high fatigue strength. However there is wide scatter in the powder consolidated properties which is due to crack initiation at sub-surface features that give a shorter life in the occasional test-piece. These features can be linked to the powder handling process and much progress is being made to eliminate them completely to raise the minimum fatigue response to a high level.

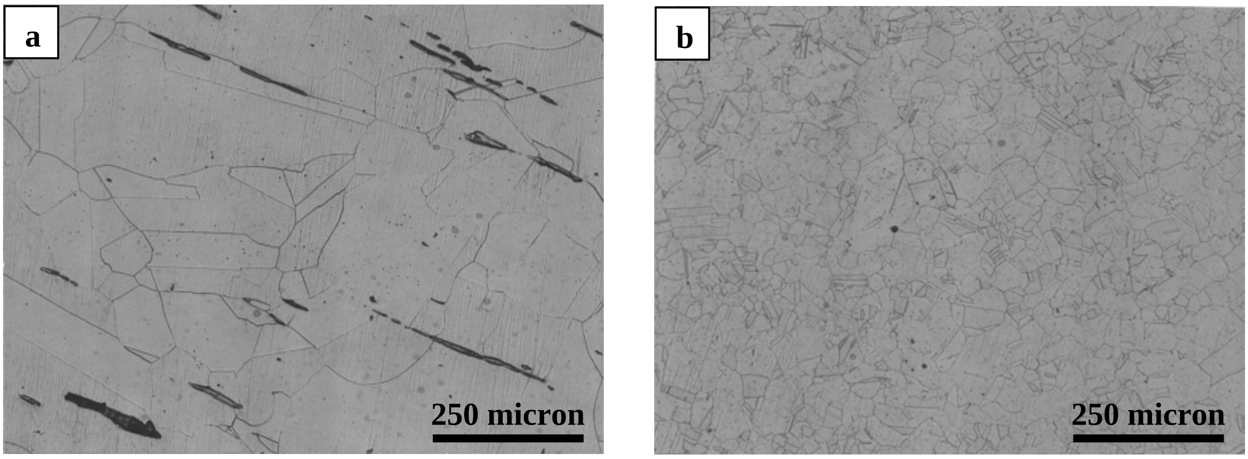

Figure 9: Comparison of (a) Forged and (b) Powder HIP'ed Stainless Steel 316L Microstructures.

The microstructural and property improvements are not restricted to the titanium alloy Ti6/4, as can be seen in the comparison of wrought and powder HIP'ed 316L stainless steel in Figure 9. Rolls-Royce has been involved in the manufacture of large steel pressure vessels from powder for almost 20 years and the typical forged component has been found to have a much coarser grain size of ASTM E112 Number 2 compared to Number 5 in the powder product [3,4,5]. The coarse forged inclusions are also greatly reduced in population and are of a more benign, rounded geometry. These features are a key aspect of the observed material performance where 0.2% proof strength, ultimate tensile strength and elongation at room temperature are considerably raised to 240MPa, 550MPa and 58% compared to the wrought

specification of 172MPa, 483MPa and 40%. Thus there are clear advantages of applying this material to military aero-engines if economical manufacture can be applied.

It has also become apparent that new materials can be released from the shackles of established manufacturing routes whilst achieving a similar enhancement in performance. An example is the burn resistant beta titanium alloy recently developed by the Birmingham IRC and Rolls-Royce [6-11] that has many attributes such as burn resistance, weldability, high ductility, and low density compared to steel, but suffers from being difficult to forge and from imparting low tool life during machining. Powder HIP consolidation removes the need for forging, and net-shape manufacture eliminates most machining operations to make the alloy economically feasible. Yet again microstructural refinement, as shown in figures 10, boosts the tensile 0.2% proof strength and elongation, in this case from 900MPa and 8% in the forging to 1060MPa and 22% for powder product. In addition, the large carbide particles scattered throughout the forged section become finely distributed in the powder HIP'ed section, thus eliminating a major cause of tool wear during cutting as well as conferring better creep resistance due to carbide strengthening of the grain boundaries.

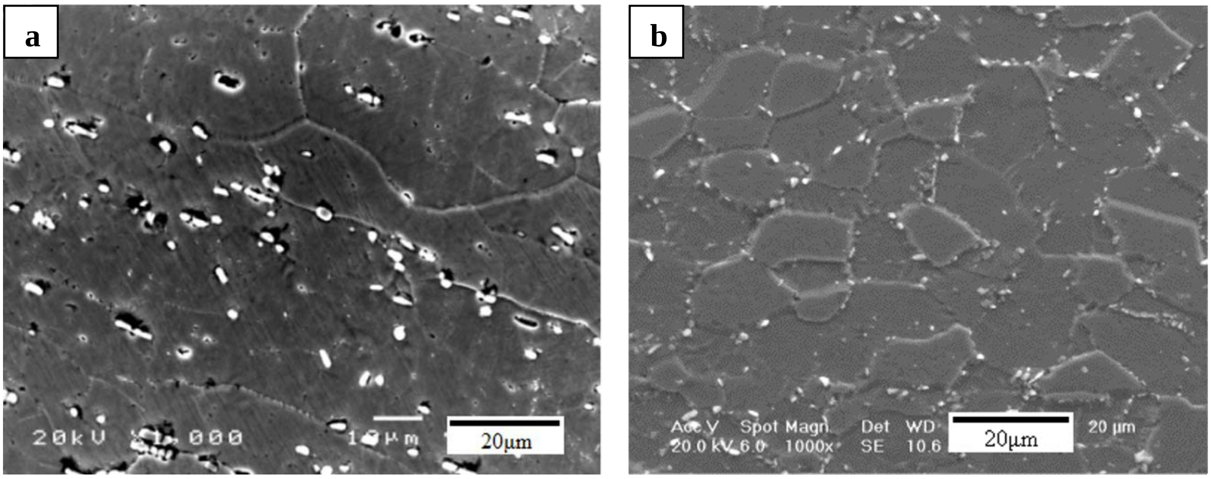

Figure 10: Comparison of (a) Forged and (b) Powder HIP'ed Burn Resistant Beta Ti Microstructures.

3.2.1 Metal Injection Moulding

Metal powders for the MIM process are mixed with thermoplastic binders and plasticisers to obtain a homogeneous feedstock in the form of pellets. The spherical metallic particles are normally in the range of 5-15μm and represent around 70% by volume of the mixture which is fed as thermoplastic material into injection moulding machines working at temperatures of 100°C to 250°C. The resultant 'green' parts have the geometric features of the finished article, apart from being enlarged, and are rigid enough to be handled. During the debinding stage, the binder and plasticisers are mostly removed and remaining traces are purged during the subsequent sintering operation. Debinding is usually performed by thermal decomposition and evaporation, chemical decomposition, or extraction with liquid chemicals. Sintering takes place in a vacuum or protected atmosphere furnace and causes a linear shrinkage to achieve 95-99% density in the part. This is normally the finished condition ready to be assembled or to undergo secondary operations such as surface hardening. For aero-space components it may be necessary to HIP the sintered part to reach full densification, made possible because the fine residual porosity is not surface connected.

Metal injection moulding (MIM) is now a well established manufacturing technique that is highly developed for most types of steel and has long serviced the auto industry with very low cost parts [12]. However MIM has also gained a foothold for precision components such as the electronic and medical

industries, and is beginning to introduce other materials potentially of interest to the aero-engine business such as the nickel superalloy 718 and titanium Ti6/4. Unfortunately reactive alloys such as those of titanium are readily contaminated with residuals from the binder and sintering in furnaces, even at high vacuum, usually results in high oxygen pick up. There is significant research effort underway in research laboratories across the world to address these problems so as to exploit the potentially large market for small Ti components.

A tolerance band of ±0.3% of the nominal dimension can be regarded as a good guideline for designing MIM parts so it is surprising that this process has not already been used to reduce costs in aero-engines. The main restriction for the use of MIM is component mass and cross-section which are generally quoted as a maximum 100g and preferably less than 5mm and certainly no more than 10mm thickness. This is due to a number of reasons, notably the accuracy of predicting the shape of the green component, maintaining the green component shape on removal from the forming die, supporting the green component during debinding and sintering, the need to remove binder from the centre of the green component, and the prevention of cracking during sinter shrinkage. There are also other design rules such as avoiding sharp internal corners and trying to maintain an even cross-section so as to achieve a uniform debinding and shrinkage without distortion.

The obvious major component application in an aero-engine would be small stators and perhaps even blades depending on whether the required fatigue lives can be obtained. However there are numerous minor components such as small brackets that could be targeted with considerable cost and weight saving. One problem could be the relative small number of components required by the aero industry, probably of the order of tens of thousands, rather than the millions per year ordered from the main MIM suppliers, for example, by the auto-industry. Consequently small to medium size companies are more suited to the aero-supply chain and the tooling cost would need to be amortised over fewer components.

Rolls-Royce has carried out a trial manufacture of a simulated stator shape in 316L stainless steel as a possible cost reduction exercise for a military engine. The tensile properties that can be achieved in the as MIM'ed state are 170MPa yield, 515MPa UTS and 50% elongation which are better than the wrought equivalent. The component cost reduces as the number required increases although in terms of absolute cost even small batch sizes are relatively cheap; £13.00 each for 100 off, £4.98 each for 500 off, £3.55 each for 1000 off, £2.75 each for 5000 off, etc. Metal injection moulding dies for the stator, see figure 11, were made using powder bed laser powder processing, figure 1, to alleviate the tooling costs and lead times. As well as making the process more economically feasible, this also facilitates rapid prototyping.

Figure 11: Powder Bed Laser Processed MIM Tooling for a 316L Stainless Steel Stator.

4.0 SUMMARY

Net-shape powder consolidation has a major role to play in reducing the cost and environmental impact in the manufacture of future military engines from small intricate to very large and complex components. Additive manufacturing will continue to become established and will increase the scope of repair techniques thus reducing engine life cycle costs and lessening the load on the manufacture of replacement parts. The pressure to introduce net-shape additive and consolidation processes will grow as the world's resources become more and more stretched over the next few decades coupled with the increasingly obvious need to improve the environment. However the most powerful driver will be the constant endeavour of the aero-engine business to reduce costs in support of the customer.

5.0 REFERENCES

[1] The Development of Powder Consolidated Components for the Gas Turbine Engine. W Voice, M Hardy, D Rugg. PM-2004 Powder Metallurgy Conference. Vienna. October 2004.

[2] The Role of Net-Shape Manufacture Reducing Life Cycle Costs of Gas Turbine Components. D Rugg, D Fray. TMS Conference (The Minerals, Metals & Materials Society), 2004

[3] Hot Isostatic Pressing of Austenitic Stainless Steel Powders for Pressure Retaining Applications. W B Burdett, A Gilleland, J Holbourn. Proceedings of International Conference on Pressure Vessel Technology (ICPVT-10), 6 – 10 July 2003, Vienna, P197 – 202.

[4] Hot Isostatic Pressing of Austenitic Stainless Steel Powders for Pressure Retaining Applications. W B Burdett, P Hurrell, A Gilleland. Proceedings of 2004 ASME/JSME Pressure Vessels and Piping Division, July 25 – 29 2004, San Diego CA.

[5] Hot Isostatic Pressing of Type 316l Powder for a Pressure Retaining Component. W B Burdett, C T Watson. Proceedings of PVP-2005: ASME Pressure Vessels and Piping Division, 17-21st July 2005, Denver.

[6] Y.G. Li, P.A. Blenkinsop, M.H.Loretto, N.A. Walker, Mat.Sci. & Tech., 1999, 15, 151.

[7] Y.G.Li & P.A. Blenkinsop, European Patent No. EP1002882B1

[8] Y.G. Li, P.A. Blenkinsop, M.H.Loretto, D. Rugg, W.E.Voice, Acta.Mat., 1999, 47, 2889.

[9] Burn Resistant Titanium Alloy (BuRTi). W E Voice. Ti-2003 Conference, Hamburg, 2003.

[10] Surface Integrity of a Burn Resistant Ti alloy (Ti-25V-15Cr-2Al-0.2Cwt.%) after High Speed Milling and Creep Feed Grinding. D Novovic, D K Aspinwall, R C Dewes, W E Voice, P Bowen. Ti-2003 Conference, Hamburg 2003.

[11] The Burn Resistant Alloy Ti-25V-15Cr-2Al-0.2C and its Potential Application in Aero-Engines. X Wu, W E Voice. San Antonio. October 2006.

[12] Metal Injection Moulding of Aerospace Components. David Heck. Proceedings of IMEC, Sheffield, UK. May 2005.

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MEETING DISCUSSION – PAPER NO: 1

Author: W. Voice

Discusser: V. Samarov

Question: What kind of qualification and certification procedures will be needed to accommodate the net shape processes at Rolls Royce?

Response: Standard Rolls Royce Materials and Processing Validation procedures would need to be followed leading to component engine demonstration.

Discusser: J. Allen

Comment on preceding question: The general case is summarized by the concept of manufacturing a "hybrid" component. Where "hybrid" is defined as a component which is a fabrication where each primitive shape of the component is manufactured by the most appropriate method for that component.

Discusser: J-P. Immarigeon

Question: Which processing route is used to produce the titanium alloy powder used at Rolls Royce for production of hot isostatically pressed components?

Response: The PREP route has been employed so far.

Discusser: D. Dicus

In future would you expect to combine the PHIP process to make engine cases and use the SMD process to add features or would you expect to combine these processes or others in some other fashion to achieve the most economic route?

Response: Nothing can be ruled out in this respect to make the processing more economic. However SMD might be better employed in making the PHIP tooling.

Discusser : C. Bampton

Question: 1. Will Rolls Royce become comfortable enough with net shape powder HIP to apply the technology to rotating components? 2. Is the real constraint the increased difficulty of non-destructive inspection?

Response: 1. Possibly for UAV's but larger engines will require a lot of effort to ensure safety is not compromised. 2. Refined inspection techniques are being developed and are being aided by the refined microstructures obtained from powder processing that give high signal to noise ratios.

Discusser: A. Pinkerton

Question: 1. Do you see Rolls Royce ever using powder methods for critical components? 2. What changes to existing processes would be necessary in order for Rolls Royce to use powder methods for critical components?

Response: 1. Not in the foreseeable future apart from UAV's. 2. Powder consolidated billets that are subsequently forged are currently being used for discs. However directly consolidated parts would require reliably clean powder sources, efficient inspection techniques and proven lifing models.

Discusser : S. Savage

Question: 1. Can cost reduction be quantified; e.g. comparing a compressor case (presently near net shape castings) with a near net shape P/M component? 2. Are there any additional benefits from P/M (resulting from the refined manufacture); e.g. fatigue or corrosion resistance?

Response: 1. Cost assessment models can be employed to predict component costs from new processing routes. 2. Fracture toughness, tensile elongation and improved inspection are the major additional benefits.

Discusser: J.P. Immarigeon

Question: What type of titanium alloy powder was used in your evaluations?

Response: Plasma rotating electrode processed (PREP) powder.